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4 **Prediction of the Arctic Oscillation in Boreal Winter by Dynamical**

5 **Seasonal Forecasting Systems**

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33 **Key Points**

- 34 ● Seasonal prediction skill of the Arctic Oscillation in boreal winter
35 ● Prediction skill change depending on period

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38 **Abstract**

39 This study assesses the prediction skill of the boreal winter Arctic Oscillation (AO) in the
40 state-of-the-art dynamical ensemble prediction systems (EPSs): the UKMO GloSea4, the
41 NCEP CFSv2, and the NASA GEOS-5. Long-term reforecasts made with the EPSs are used
42 to evaluate representations of the AO, and to examine skill scores for the deterministic and
43 probabilistic forecast of the AO index. The reforecasts reproduce the observed changes in the
44 large-scale patterns of the Northern Hemispheric surface temperature, upper-level wind, and
45 precipitation according to the AO phase. Results demonstrate that all EPSs have better
46 prediction skill than the persistence prediction for lead times up to 3-month, suggesting a
47 great potential for skillful prediction of the AO and the associated climate anomalies in
48 seasonal time scale. It is also found that the deterministic and probabilistic forecast skill of
49 the AO in the recent period (1997-2010) is higher than that in the earlier period (1983-1996).

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52 **Index Terms and Keywords**

53 Climate variability; Coupled models of the climate system

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56 **1. Introduction**

57 The Arctic Oscillation (AO, *Thompson and Wallace* [1998]), which is characterized by a
58 periodic exchange of the atmospheric mass field between the Arctic and the rest of high
59 latitudes, is an important mode of climate variability in the Northern Hemisphere. When the
60 Arctic region has anomalously higher atmospheric mass – the negative phase of the AO, the
61 circumpolar jet stream weakens and shifts southward, causing abnormally severe winters in
62 the mid-latitude [*Thompson and Wallace*, 2000; *Higgins et al.*, 2002; *Wettstein and Mearns*,
63 2002]. Regarding its profound impacts on winter climate over the Northern Hemispheric mid-
64 and high-latitude areas, the accuracy of the seasonal prediction over these regions seems to be
65 tied strongly with our ability to predict the AO. This calls for a systematic assessment of
66 prediction skill of the AO using forecasts made with operational forecast systems.

67 While the nature of the AO and the physical mechanisms under the phenomenon have
68 been extensively studied [*Limpasuvan and Hartmann*, 2000; *Lorenz and Hartmann*, 2003;
69 *Polvani and Waugh*, 2004; *Cohen et al.*, 2010; *Kim and Ahn*, 2012, among many others],
70 studies focusing on the seasonal predictability or the prediction skill of the AO are
71 surprisingly rare in the literature. To our knowledge, only one study examined prediction skill
72 of the AO exclusively [*Riddle et al.*, 2013], although *Arribas et al.* [2011] and *Kim et al.*
73 [2012] assessed forecast skill of the North Atlantic Oscillation (NAO) as one of climate
74 variability investigated. In *Riddle et al.* [2013], it is found that the National Centers for
75 Environmental Prediction (NCEP) coupled forecast system model version 2 (CFSv2, [*Saha et*
76 *al.* 2013]) is capable to forecast the wintertime AO up to forecast lead time more than 2
77 months. They suggested the hardly resolved process in the model associated with the
78 stratospheric pathway of atmosphere related to the propagation linked to October Eurasian
79 snow cover.

Motivated from the above, this study evaluates the AO prediction performance for three state-of-the-art seasonal forecasting systems, the UK Met Office Global Seasonal forecasting system version 4 (GloSea4) [Arribas *et al.*, 2011], the NCEP CFSv2, and the National Aeronautics and Space Administration (NASA) Goddard Earth Observing System Model, Version 5 (GEOS-5) AOGCM [Rienecker *et al.* 2011]. These systems have been developed independently with quite different model formulations and initialization processes. By carefully examining multi-decadal reforecasts produced with these forecasting systems, we aim at quantifying the current level of AO prediction skill in modern seasonal forecast systems, and at identifying the differences in skill that are presumably due to the differences in model formulation and the initialization processes.

Section 2 describes data and methodology used in this study. Prediction skill of the AO in the three reforecast datasets will be presented in Section 3. Summary and conclusions are given in Section 4.

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94 **2. Data and Methodology**

The following data were used in this research: the reforecasts from GloSea4 (1996–2009), from CFSv2 (1982–2010) and from GEOS-5 (1981–2012). The detailed descriptions of each reforecasts are given in Table 1. Three ensemble members of GloSea4, perturbed by stochastic physics, are initiated at fixed calendar dates of each month, and integrated for 7 months. The reforecasts of CFSv2 are initialized every 5 days (from all 4 cycles of the day) beginning with Jan 1st of each year by using 9-hour coupled guess field. The GEOS-5 seasonal forecasts consist of a single ensemble member initialized every 5 days and additional ensemble members, generated through coupled model breeding and independent

103 perturbations in the atmosphere and ocean, produced in day closest to the beginning of the
104 month.

105 For this study, only ensemble members that were initialized in November and first
106 available day in December were used to evaluate the prediction skill of the boreal winter AO.
107 Note that the number of ensemble members is different for the different systems (Table 1).
108 The used ensemble members are 15 for GloSea4, 28 for CFSv2, and 19 for GEOS-5.

109 For verification, we used the Modern Era Retrospective-Analysis for Research and
110 Applications (MERRA, [Rienecker *et al.* 2011]) atmospheric reanalysis. MERRA has a
111 spatial resolution of $1/2^{\circ}$ (latitude) \times $2/3^{\circ}$ (longitude), with 72 vertical levels. We note that
112 our results are not dependent on the choice of reanalysis. Almost identical results for the AO
113 index derived from an empirical orthogonal function (EOF) analysis using sea level pressure
114 (SLP) are obtained using ERA-Interim (the correlation coefficient of DJF AO index between
115 ERA-Interim and MERRA is larger than 0.99). Additionally, data from Global Precipitation
116 Climatology Project (GPCP, [Adler *et al.*, 2003]) are used to validate precipitation from the
117 models.

118 To obtain characteristic pattern and time variation of the observed AO, the EOF analysis
119 was performed with seasonal-mean (DJF), Northern hemispheric (north of 20°N) sea level
120 pressure data from MERRA. The resulting first EOF represents the AO mode and the PC
121 time series associated with the first EOF exhibit interannual variation of the AO mode. The
122 three reforecast datasets are evaluated with respect to i) the fidelity to reproduce the observed
123 pattern of the AO, and ii) the capability to forecast the observed interannual variation of the
124 AO.

125 In order to evaluate the AO patterns reproduced by the prediction systems, the same EOF

126 analysis was applied to each ensemble member¹. After obtaining the AO mode (i.e. 1st or 2nd
127 EOF) from each ensemble member, we took an ensemble average of the AO patterns, after
128 multiplying standard deviations of their PCs. When we compared these AO pattern from the
129 reforecast datasets, we multiplied standard deviation of first PC to the observed AO pattern.
130 Anomalous pattern of other variables associated with the AO were obtained by regressing the
131 variables onto the PC time series of the AO mode for each ensemble member, and then
132 averaging the regressed patterns over the ensemble.

133 To assess the prediction skill of the AO using the reforecast dataset, either seasonal or
134 monthly averaged forecasted SLP anomaly was projected onto the observed AO pattern. The
135 resulting time series, after normalized by its own standard deviation, is then used for the
136 forecast skill assessment. Temporal correlation coefficient between the observed and
137 forecasted AO indices represents the prediction skill in this study. The forecasted AO indices
138 were obtained by averaging the normalized time series from each ensemble member, and we
139 tried two ways of ensemble averaging. The first one is a simple averaging, in which all
140 ensemble members have equal weighting. The second way bases on an argument that
141 ensemble members whose initialization time is closer to target season should have bigger
142 weightings. In this method, we set an arbitrary weighting (100) to the ensemble member
143 whose initialization time is closest to the target season (Dec. 2nd), and reduced the weighting
144 as the initialization time becomes earlier (2 per day). Because the results from both methods
145 showed similar forecast skill (not shown), we here present only the results obtained with the
146 second averaging method. The persistent forecast provides a baseline forecast, and we
147 consider a prediction skill useful only when it exceeds that of the persistent forecast.

¹ In most cases, an AO-like pattern emerged as the first EOF. In some cases the second mode was used. This was done if the pattern correlation between the second EOF and the AO pattern from MERRA is higher than that of the leading EOF (this never occurred for GloSea4, it occurred once for GEOS-5, and it occurred six times for CFSv2)

148 The Relative Operating Characteristic score (ROC, [Mason, 1982]) is used as a skill
149 metric for probabilistic forecast of the AO index. The ROC scores for the upper tercile (i.e.
150 positive AO) and lower tercile (i.e. negative) were evaluated with probability thresholds
151 ranging from 0% to 100% with a 20% interval. In general, the ROC score above 0.5 indicates
152 skill better than climatology. As far as we are aware, this is the first assessment of
153 probabilistic forecast skill of the AO using the coupled seasonal forecast. On the other hand,
154 the probabilistic forecast skill of the NAO was studied using the ECMWF system 2 [*Müller*
155 *et al.*, 2005].

156

157 **3. AO Prediction**

158 Figure 1 compares the AO SLP patterns represented in the three prediction systems to
159 that obtained from MERRA. MERRA shows a zonally symmetric pattern with clear opposite
160 signed anomalies between the Arctic and the mid-latitude oceans (North Pacific Ocean and
161 North Atlantic Ocean). All prediction systems are able to reproduce this pattern fairly well,
162 exhibiting action centers close to that of MERRA. The pattern correlations between MERRA
163 and each forecast have comparable values ranging between 0.86 and 0.90. The prediction
164 systems, however, commonly underestimate amplitude of the peaks, especially over the
165 North Atlantic and the Kara Sea. Compared to other prediction systems, GEOS-5 exhibits
166 more realistic SLP anomaly pattern over the Kara Sea and the northern Siberia. The AO
167 mode explains about 37 and 39% of total interannual variability in GEOS-5 and GloSea4,
168 respectively, which is close to the observed value (41%). The percentage variance explained
169 by the AO mode from CFSv2 is somewhat lower than that of others; this might be due to the
170 greater frequency of mixing the AO signal with the 2nd EOF mode.

171 Spatial patterns of surface temperature, 200 hPa zonal wind and precipitation anomalies
172 associated with the AO mode from each reforecast are shown in Figure 2. The north-south
173 oriented patterns of anomalous surface temperature are represented over Eurasia and North
174 America in MERRA (Figure 2a). This surface temperature anomaly pattern is reasonably
175 reproduced in the reforecasts over land (Figures 2b-d), although its amplitude is
176 underestimated. The amplitude of the temperature variability over Siberia is more realistic in
177 GEOS-5 than those of the other systems, and this might be linked to the more realistic
178 pressure pattern over Siberia and the Kara Sea (Figure 1d). The upper level zonal wind
179 pattern from the forecast systems is consistent with that of MERRA with high statistical
180 significance, describing a realistic modulation the jet stream corresponding to the phase of the
181 AO (Figs. 2e-h). Nevertheless, there are system-dependent biases such as shifts in the centers
182 of variability that correspond to biases in the SLP variability. For example, variability center
183 of GloSea4 and GEOS-5 shifted to westward in the North Pacific Ocean. Consistent to the jet
184 stream shift, the precipitation is enhanced in high-latitudes positive phase of the AO, but the
185 amplitudes of the forecasts are lower than observation. The forecast systems commonly fail
186 to capture the precipitation anomaly in the East Asia (Figs. 2i-l).

187 Above results demonstrate that the prediction systems are able to reproduce the observed
188 AO pattern at least to some extent. From now on, we focus on the prediction skill. Note that,
189 as described in Section 2, we use a single AO pattern obtained from MERRA, not each
190 system's own one, for this purpose. The time series of the recent AO index (1997-2010) from
191 MERRA and reforecasts are shown in Figure 3a. The reforecasts show a reasonable
192 prediction of the seasonal mean AO index. This includes the anomalously negative value in
193 2010, although GloSea4 and GEOS-5 underestimate the intensity of negative anomaly.
194 Ensembles of the three prediction systems commonly show a large spread, though they tend

195 to show relatively small spread in several years. Table 2 shows the correlation coefficients
196 between the AO index of MERRA and of each reforecast. Note that CFSv2 and GEOS-5
197 show much higher correlations for recent period (1997-2010) compared to those for earlier
198 period (1983-1996). Similar to the skill of the deterministic forecasts of the AO index, the
199 skill of probabilistic forecast also show substantial score changes between the two periods
200 (Figure 4). Each reforecast shows marginal prediction skill for both positive and negative
201 phases of the AO for 1997–2010 (all of ROC scores exceed 0.6), while the ROC scores for
202 1983–1996 (lower than 0.5 in case of upper tercile) are lower than those for the recent 14
203 years.

204 Figures 3b-d show month-to-month temporal correlation coefficients for December-
205 March along with corresponding results with the persistence forecast. Forecasts initialized in
206 November show higher temporal correlation coefficients in winter than persistent for 1997-
207 2010, while the skill of dynamical predictions do not consistently exceed that of persistence
208 forecast after February. The prediction skill for 1983-1996 is comparable to persistence after
209 December consistent with lower seasonal mean prediction skills during early period (1983-
210 1996) indicated in Table 2. The reason for the lower prediction skill of GloSea4 in January
211 and February is not clear, but it seems to be related to the model bias or influenced by
212 relatively small number of ensemble member. The GloSea4 shows higher prediction skill in
213 case of using forecast-driven EOF to derive AO index ($r = 0.54$ for DJF-mean compared to
214 0.42 in Table 2), which implies model bias of the EOF pattern obscured the prediction skill of
215 the AO.

216

217 **4. Conclusion**

218 This study examined the skill of AO predictions using reforecast datasets made with
219 three state-of-the-art coupled ensemble prediction systems. The study in particularly focused
220 on wintertime AO predictions using a set of reforecasts initialized around November over
221 multiple years. The three prediction systems all include interactive land, ocean and sea ice
222 components coupled with the atmosphere, although the details of the formulations and the
223 initialization processes are substantially different among the systems. Our results show that
224 the seasonal forecast systems exhibit significant skill at predicting the AO up to 3 months of
225 forecast lead time for recent 14 years. This suggests that useful AO predictions could be
226 issued in November for the following winter.

227 Our results highlight two aspects of the AO prediction problem. First of all, seasonal
228 prediction systems are able to reproduce the basic AO phenomenon itself, with high pattern
229 correlations in SLP ranging from 0.86 to 0.90. The forecast systems also demonstrate realistic
230 patterns of anomalous surface temperature, upper-level wind, and precipitation that are
231 associated with the AO, implying that those systems are able to resolve the key physical and
232 dynamical processes accompanied by the AO. Secondly, the seasonal prediction systems
233 have capability to forecast year-to-year variations of the AO, including the recent extreme
234 occurrences of the AO. The prediction skill does differ among the three systems, and this
235 likely reflects differences in the parameterizations and initialization processes of each system.
236 There is considerable spread among the ensemble members, suggesting the possibility of
237 future improvements in AO predictions.

238 The prediction skills for 1997–2010 were higher than the previous 14 years for both the
239 deterministic and probabilistic predictions. *Riddle et al.* [2013], who found this change earlier
240 from CFSv2 reforecasts, speculated that the difference was caused by systematic errors and
241 bias associated with the initialization prior to 1998. However, we cannot exclude other

242 possibilities (e.g., a mean state shift favoring greater predictability of the AO during the
243 recent period). For example, *Li et al.* [2013] suggested a strengthening in the relationship
244 between the AO and the El Niño-Southern Oscillation (ENSO) after the mid-1990s, with
245 possible links to interannual variability of sea ice. The correlation coefficient between DJF-
246 mean AO index in this study and the Oceanic Niño Index of NOAA from the website
247 (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) was
248 0.02 for 1983-1996 and -0.59 for 1997-2010, suggesting a possible contribution of the
249 changes in ENSO-AO coupling to the prediction skill change of AO index. It requires further
250 study to identify the mechanism for the higher prediction skill of AO from the dynamical
251 seasonal prediction in recent period.

252 *Arribas et al.* [2011] did not show significant prediction skill for NAO (which is
253 analogous to AO), while in this study we found a much higher prediction skill of the AO.
254 *Arribas et al.* [2011] used a similar analysis period with this study but GloSea4 in this study
255 used an improved version of the physical parameterizations, sea ice initialization and
256 extended vertical resolution compared to the version used in *Arribas et al.* [2011]. This
257 implies that sea ice initialization and a fully represented stratosphere may play an important
258 role in the AO prediction skill.

259 CFSv2 showed the highest AO prediction skill among the three sets of reforecasts. The
260 better performance may be associated with the 9 hour coupled initialization in CFSR, which
261 reduces the bias from each boundary, although further investigation is required to verify the
262 benefit from the coupled initialization. The AO prediction skill from the multi-model
263 ensemble (MME, $r = 0.78$ for 1997–2010) was comparable to the skill from CFSv2, which
264 implies the MME was not adding much benefit in this case.

265 The short time period over which the prediction skill was evaluated, makes it difficult to

266 assess any modulation of the AO from long-term variability such as the Pacific Decadal
267 Oscillation (PDO). For example, the higher prediction skill of the NAO in recent decades has
268 also been shown in previous studies [*Rodwell and Folland*, 2002; *Bierkens and Beek*, 2009].
269 This change in skill was also found in the AO from CFSv2 [Riddle et al., 2013]. Therefore, it
270 is not possible to affirm that the level of skill found in this study will be same in the future.

271

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344

345 **Table 1.** Summary of the seasonal forecasting systems. Abbreviations and acronyms defined
 346 as follows: Met Office Unified Model (UM), Global Forecast System (GFS), Modular Ocean
 347 Model version 4 (MOM4), Nucleus for European Modeling of the Ocean (NEMO), Met
 348 Office Surface Exchange Scheme (MOSES), GEOS-integrated Ocean Data Assimilation
 349 System (GEOS-iODAS [*Vernieres et al.*, 2012]), Climate Forecast System Reanalysis (CFSR
 350 [Saha et al., 2010])

	GloSea4	CFSv2	GEOS-5
Reforecast period	1996-2009	1981-2010	1981-2012
Model	UM version 7.6, (atmosphere, ocean, land, and sea ice)	GFS, MOM4, Noah land model, and 3- layer sea ice model	GEOS-5, MOM4, Catchment Land Surface Model [Koster et al. 2000], and CICE
Horizontal resolution			4.0
Vertical levels	N96L85 (145×196)	T126L64 (181×360)	1°×1.25° (181×288)
Initial condition	ERA-Interim (atmosphere-land) and NEMO-CICE data assimilation (ocean-sea ice)	CFSR (9h full-coupled initialization)	MERRA (atmosphere- land) and GEOS- iODAS (ocean-sea ice)

	3-member on fixed calendar dates (the 1st, 9th, 17th and 25th) of each month	4-member on every 5 days beginning with Jan 1st of each year	1-member on every 5 days with additional members for the beginning of the month [<i>Kirtman et al.</i> , 2013; <i>Ham et al.</i> , 2013]
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353 **Table 2.** Correlation coefficients between DJF-mean AO index from MERRA and each
354 forecast. Single and double asterisk indicates that the correlation coefficient is statistically
355 significant at the 95% and 99% confidence level, respectively.

	1983–1996	1997–2010	1983–2010
GloSea4	n/a	0.42	n/a
CFSv2	0.46	0.87**	0.66**
GEOS-5	0.33	0.57*	0.43*
Persistent	-0.23	0.23	-0.25

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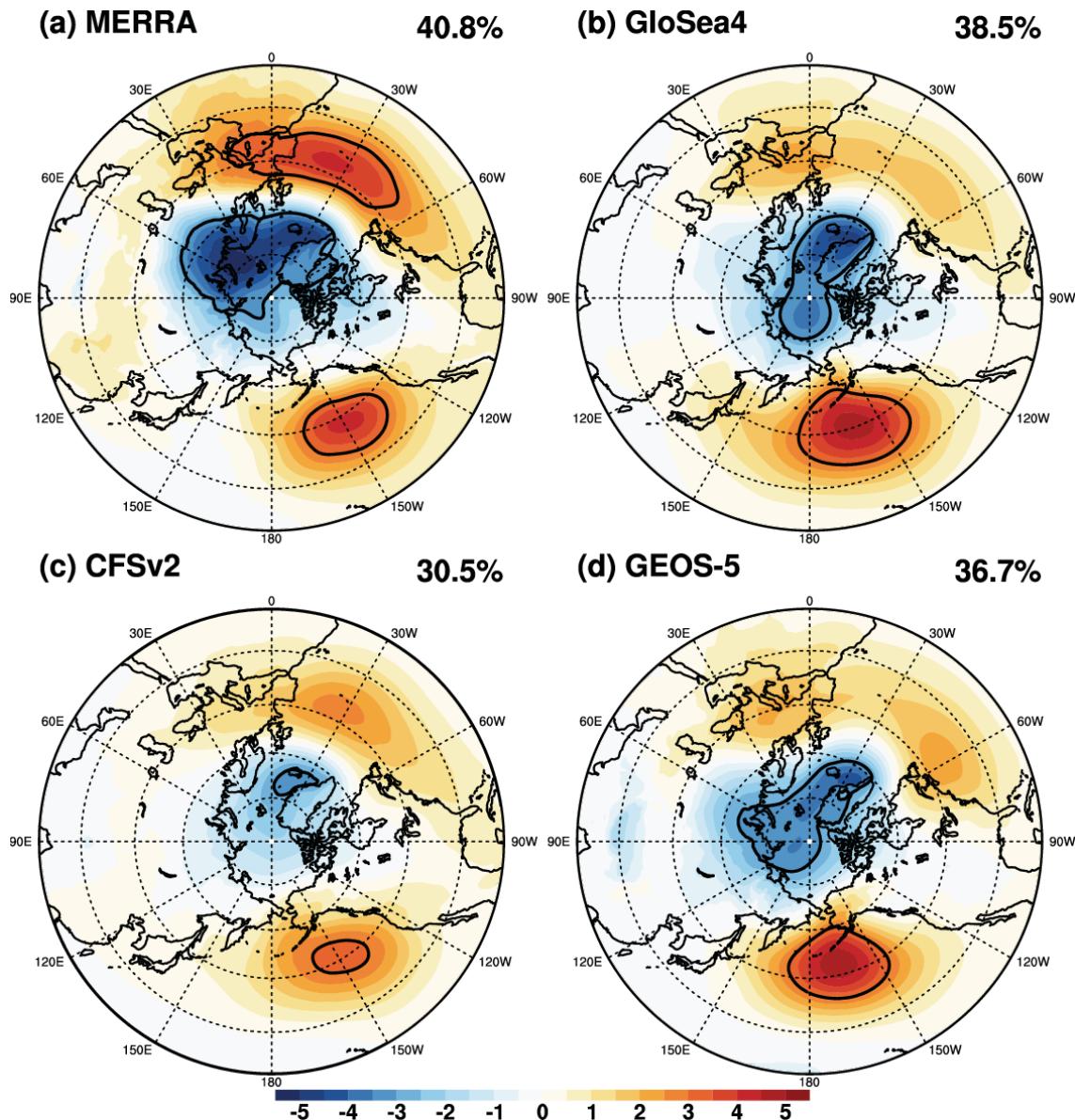
357

358 **Figure 1.** DJF mean sea level pressure anomaly regressed onto leading PC for 1997–2010 for
359 (a) MERRA, (b) GloSea4, (c) CFSv2, and (d) GEOS-5 (unit is hPa). Contour lines refer
360 absolute value equal to 3 hPa. Percentages indicate explained variance (averaged explained
361 variance from each ensemble member) from the pattern.

362 **Figure 2.** DJF mean surface temperature anomaly (1st row, unit is K), zonal wind at 200 hPa
363 anomaly (2nd row, unit is m/s), and normalized precipitation (3rd row, unitless) regressed onto
364 AO index of each forecast for 1997–2010. Precipitation anomalies are normalized by
365 monthly mean precipitation of each grid point. The dotted grids indicate statistically
366 significant more than 90% confidence levels.

367 **Figure 3.** (a) DJF mean normalized AO index of MERRA (black solid line), GloSea4 (red
368 bars), CFSv2 (blue bars), GEOS-5 (orange bars). The error bars refer ensemble spread of AO
369 index between first quarter and third quarter. Correlation coefficient of AO index as a
370 function of forecast lead month for (b) GloSea4, (c) CFSv2, and (d) GEOS-5. Black dashed
371 line refers persistent forecast by MERRA November AO index for 1979–2012, and colored
372 lines indicate prediction skill for each period. Thin horizontal dashed line refers 90%
373 confidence level for 14 years.

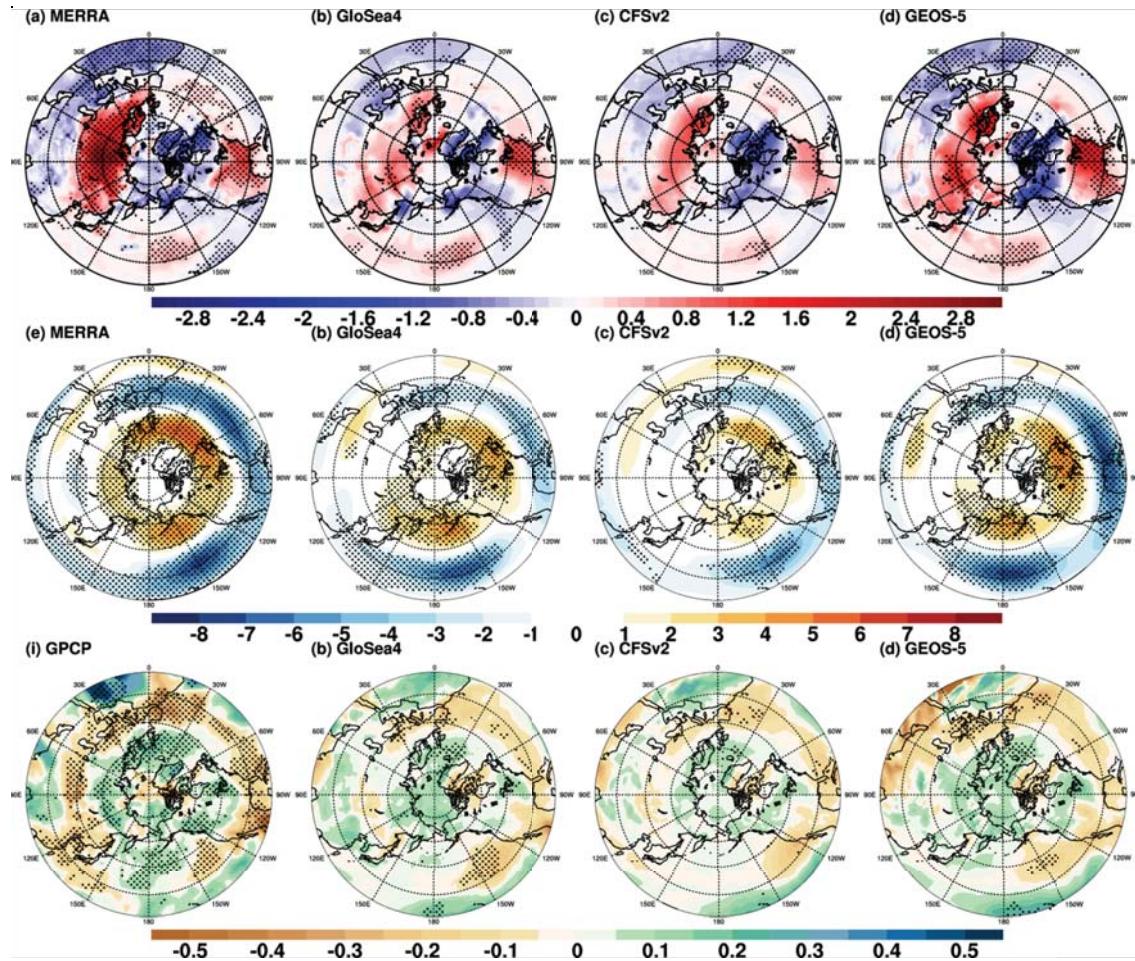
374 **Figure 4.** Sum of Relative Operating Characteristic (ROC) scores for ensemble AO index
375 prediction for upper tercile (red) and lower tercile (blue). The checkered bars indicate ROC
376 scores for 1983–1996, and the filled bars indicate ROC scores for 1997–2010.



379 **Figure 1.** DJF mean sea level pressure anomaly regressed onto leading PC for 1997–2010 for
 380 (a) MERRA, (b) GloSea4, (c) CFSv2, and (d) GEOS-5 (unit is hPa). Contour lines refer
 381 absolute value equal to 3 hPa. Percentages indicate explained variance (averaged explained
 382 variance from each ensemble member) from the pattern.

383

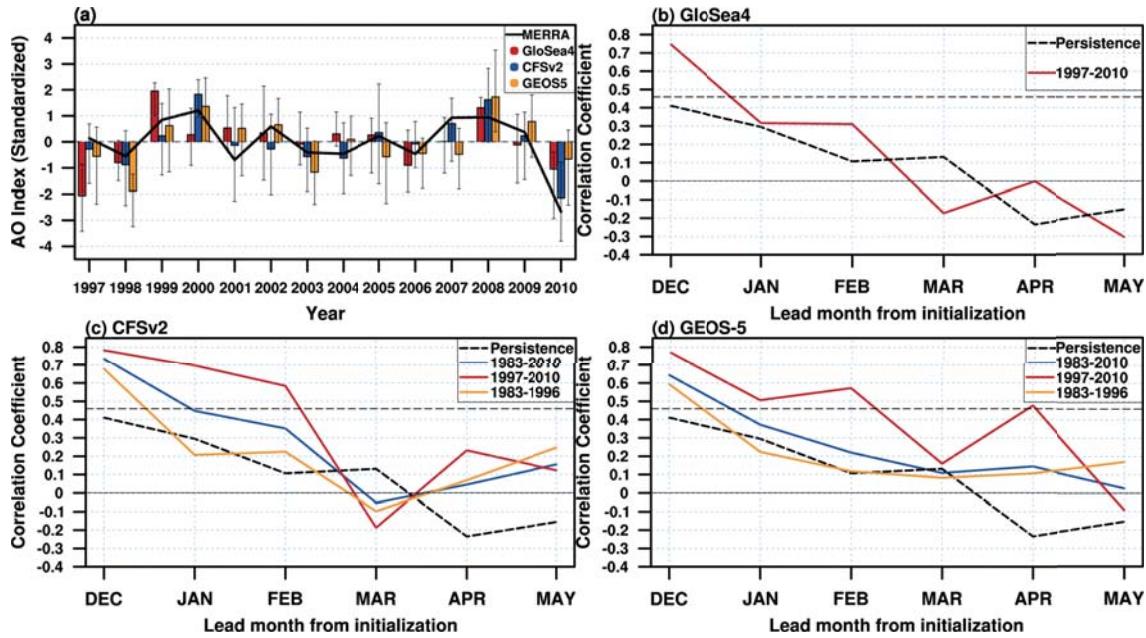
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385

386 **Figure 2.** DJF mean surface temperature anomaly (1st row, unit is K), zonal wind at 200 hPa
 387 anomaly (2nd row, unit is m/s), and normalized precipitation (3rd row, unitless) regressed onto
 388 AO index of each forecast for 1997–2010. Precipitation anomalies are normalized by
 389 monthly mean precipitation of each grid point. The dotted grids indicate statistically
 390 significant more than 90% confidence levels.

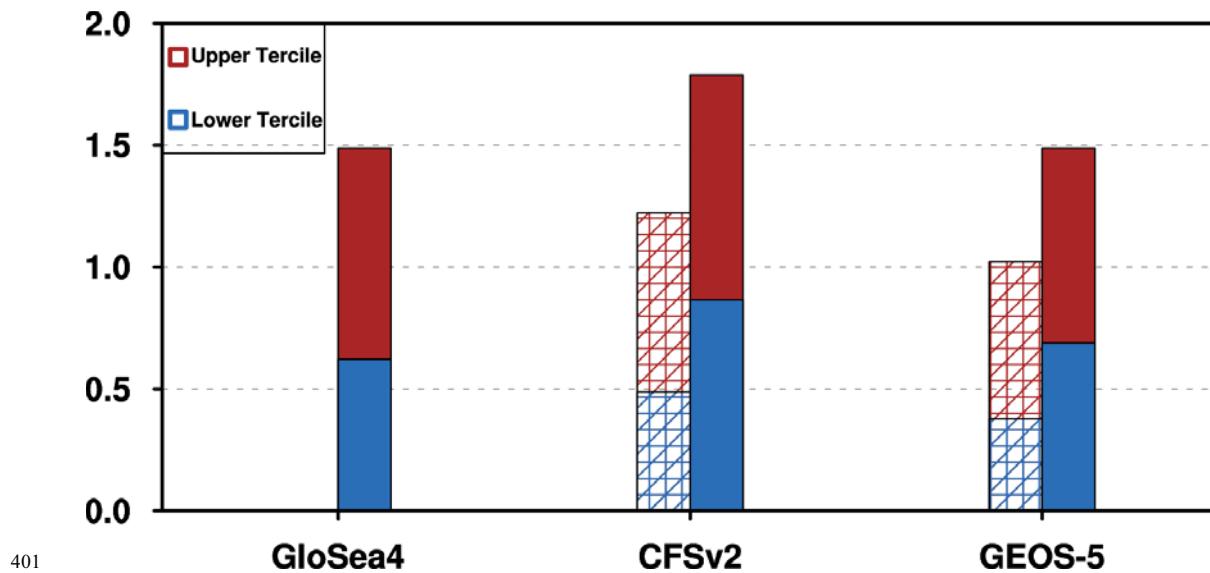
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392

393 **Figure 3.** (a) DJF mean normalized AO index of MERRA (black solid line), GloSea4 (red
 394 bars), CFSv2 (blue bars), GEOS-5 (orange bars). The error bars refer ensemble spread of AO
 395 index between first quarter and third quarter. Correlation coefficient of AO index as a
 396 function of forecast lead month for (b) GloSea4, (c) CFSv2, and (d) GEOS-5. Black dashed
 397 line refers persistent forecast by MERRA November AO index for 1979–2012, and colored
 398 lines indicate prediction skill for each period. Thin horizontal dashed line refers 90%
 399 confidence level for 14 years.

400



401 **Figure 4.** Sum of Relative Operating Characteristic (ROC) scores for ensemble AO index
402 prediction for upper tercile (red) and lower tercile (blue). The checkered bars indicate ROC
403 scores for 1983–1996, and the filled bars indicate ROC scores for 1997–2010.
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